Economic viability of pressurized solid oxide electrolysis process: a comparative analysis across industrial hydrogen applications

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Abstract:

Pressurized solid oxide electrolysis cells (SOEC) present a promising pathway for cost-effective green hydrogen production, yet systematic economic comparisons across system configurations and industrial scales remain limited. This study presents a techno-economic analysis of different plant configurations, combining three SOEC technology variants — atmospheric stack with downstream H_2 compression (ATM), pressurized stack (P-stack), and vessel-enclosed pressurized stack (P-vessel) — evaluated across two industrial use cases: steel production via direct reduced iron (14,000 kg H_2/h at 13.7 barg) and hydrogen as fuel (15 kg H_2/h at 4 barg). Air-sweep ratios (1:1, 2:1, and 23.5 mol% O_2 target) are also varied for the DRI case. The cost assessment follows a two-stage methodology: a deterministic model computes capital expenditure (CAPEX), operating expenditure (OPEX), and the levelized cost of hydrogen (LCOH), followed by a Monte Carlo sensitivity analysis (10,000 runs) evaluating economic robustness under stochastic energy price and CO_2 tax trajectories over a 20-year horizon. Results show that the SOEC stack dominates power consumption across all cases (65–97%), while electricity constitutes 72–86% of OPEX. At an electricity price of 70 EUR/MWh, the LCOH ranges from 2.91 to 4.76 EUR/kg for the large-scale DRI case, with several configurations approaching the project target of 3.0 EUR/kg, whereas the small-scale fuel case yields higher costs (4.87–5.26 EUR/kg) due to the absence of economies of scale. Under progressive grid decarbonization scenarios, the 13.7 barg DRI configurations reach LCOH values as low as 1.5 EUR/kg. The air-sweep strategy significantly impacts costs: increasing the circulation ratio from 1:1 to 2:1 raises the LCOH, while the 23.5 mol% O_2 target scenario leads to the highest costs due to elevated air compressor demand. These findings provide quantitative guidance for matching pressurized SOEC deployment to specific application requirements, confirming that production scale, electricity price, and air management strategy are the primary economic levers.

Keywords:
Pressurized solid oxide electrolyzers; techno-economic assessment; Monte Carlo analysis; levelized cost of hydrogen production.

1. Introduction

Green hydrogen production through water electrolysis is foreseen as a key enabler of industrial decarbonization. Among the available electrolysis technologies, solid oxide electrolysis cells stand out for their high thermodynamic efficiency, operating at temperatures between 700 and 900 °C where a significant share of the energy input can be supplied as heat rather than electricity. This translates into lower specific electricity consumption compared to other electrolysis technologies, such as the proton exchange membrane and the alkaline electrolyzers, making SOECs particularly attractive when coupled with industrial waste heat or renewable thermal sources.

However, many downstream industrial processes require hydrogen at elevated pressures. Conventionally, hydrogen produced at atmospheric pressure must be mechanically compressed, introducing additional capital and operating costs. Pressurized SOEC operation offers an alternative by performing electrochemical compression directly within the cell, potentially eliminating or substantially reducing downstream compression requirements [1], [2], [3]. Two design approaches have been proposed: enclosing the stack assembly within a pressure vessel (P-vessel), and pressurizing the stack itself (P-stack).

Despite the growing technical understanding of pressurized SOEC operation, comprehensive economic assessments comparing different pressurization strategies across realistic industrial scales remain scarce [1]. Most existing techno-economic studies focus on atmospheric SOEC systems or consider only a single pressurization approach. The tradeoffs between production scale, target delivery pressure, air management strategy, and configuration choice (atmospheric vs. pressurized stack vs. pressure vessel) on the levelized cost of hydrogen (LCOH) has not been systematically quantified. Furthermore, the economic robustness of pressurized configurations under uncertain future electricity prices and carbon taxation policies has also not been explored.

In this context, the present work provides a comprehensive techno-economic assessment (TEA) of pressurized SOEC hydrogen production systems across two industrially relevant use cases: steel direct reduction (14,000 kg H_2/h at 13.7 barg) and hydrogen as fuel (15 kg H_2/h at 4 barg). Fifteen plant configurations are evaluated, combining three technology variants (ATM, P-stack, P-vessel) with multiple air-sweep strategies. A deterministic cost model quantifies CAPEX, OPEX, and LCOH using modular equipment scaling, while a Monte Carlo sensitivity analysis (10,000 simulations) assesses the robustness of the economic results under stochastic electricity price and CO_2 tax scenarios over a 20-year project horizon. The influence of grid decarbonization pathways on LCOH competitiveness is also investigated.

2. Methodology

The plant configurations evaluated are listed in Table 1. They combine the three SOEC technology variants with two outlet pressure levels targets (4 and 13.7 barg), and up to three sweeping air strategies where the O_2 content in the outlet air is varied at 34 mol% (2:1 air to steam molar ratio) and 38 mol% (1:1 air to steam molar ratio), with an additional 23.5 mol% scenario considered exclusively for the DRI case. The technology variants are:

- ATM: atmospheric SOEC stack with downstream H_2 compression;
- P-stack: pressurized SOEC stack, operating at elevated stack pressure;
- P-vessel: SOEC stack enclosed within a pressure vessel.

Table 1. *Hydrogen targets case studies.*

Hydrogen industry	Configuration	H_2 target pressure (barg)	SOEL stack pressure (barg)	H_2 capacity (kg/h)
Steel-DRI	1: Pressure vessel	13.7	13.7	14000
Steel-DRI	2: P-type stack	13.7	9	14000
Steel-DRI	3: ATM	13.7	0	14000
H_2 as fuel	1: Pressure vessel	4	4	15
H_2 as fuel	2: P-type stack	4	4	15
H_2 as fuel	3: ATM	4	0	15

Figure 1 shows the SOEC flowsheet scheme and the simulations were conducted in Aspen Plus v14. A current density of 1 A/cm^2 and a utilization factor of 80% has been considered on the models. For each configuration, the mass and energy balances including SOEC stack power consumption, hydrogen and oxygen production rates, air and steam flow rates, heat exchanger duties with inlet and outlet temperatures, and compressor/pump power requirements. These data serve as direct inputs to the cost model.

A single SOEC stack producing approximately 0.5 kgH_2/h. To reach the target production capacity of each use case, a modular scaling procedure is applied. The air compressor, heat exchangers, furnace, and water pump are shared balance-of-plant (BoP) items. The modular hierarchy that determines number of BoP is structured as follows: 4 stacks form one module, 4 modules (16 stacks) are grouped into one pressure vessel, and 316 modules share one BoP system. Discrete equipment counts are obtained by rounding up to the nearest integer, ensuring the nominal H_2 target is always met.

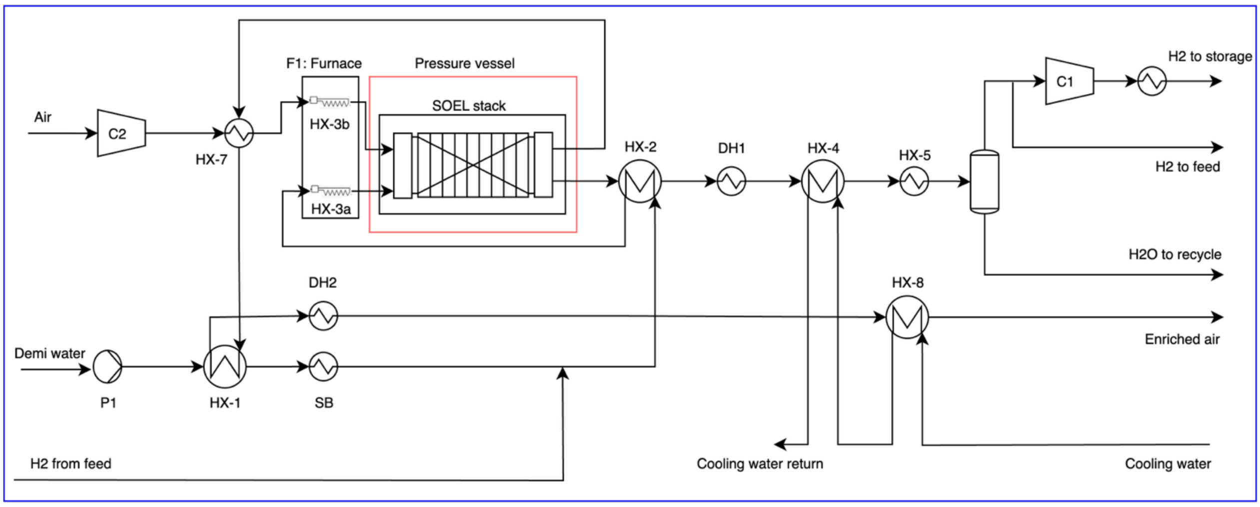

Figure 1. *SOEC flowsheet.*

The techno-economic assessment follows a two-stage sequential methodology. In the first stage, a deterministic cost model computes capital expenditure (CAPEX), operating expenditure (OPEX), and the Levelized Cost of Hydrogen for each of the 15 plant configurations considered. In the second stage, a probabilistic sensitivity and risk analysis is applied to the deterministic results using Monte Carlo simulation, stochastic cost trajectory generation, and incremental Net Present Value (iNPV) comparisons.

2.1. TEA framework

The overall TEA workflow is summarized in Fig. 2. Briefly, the framework begins with an Excel interface that centralizes design data for all configurations. The workflow sequentially imports cost functions, applies the modular scaling, and computes deterministic CAPEX, OPEX, and LCOH. The Monte Carlo module then generates stochastic cost trajectories for electricity, water, H_2 selling price, and CO_2 tax, and produces probabilistic output distributions for LCOH and iNPV.

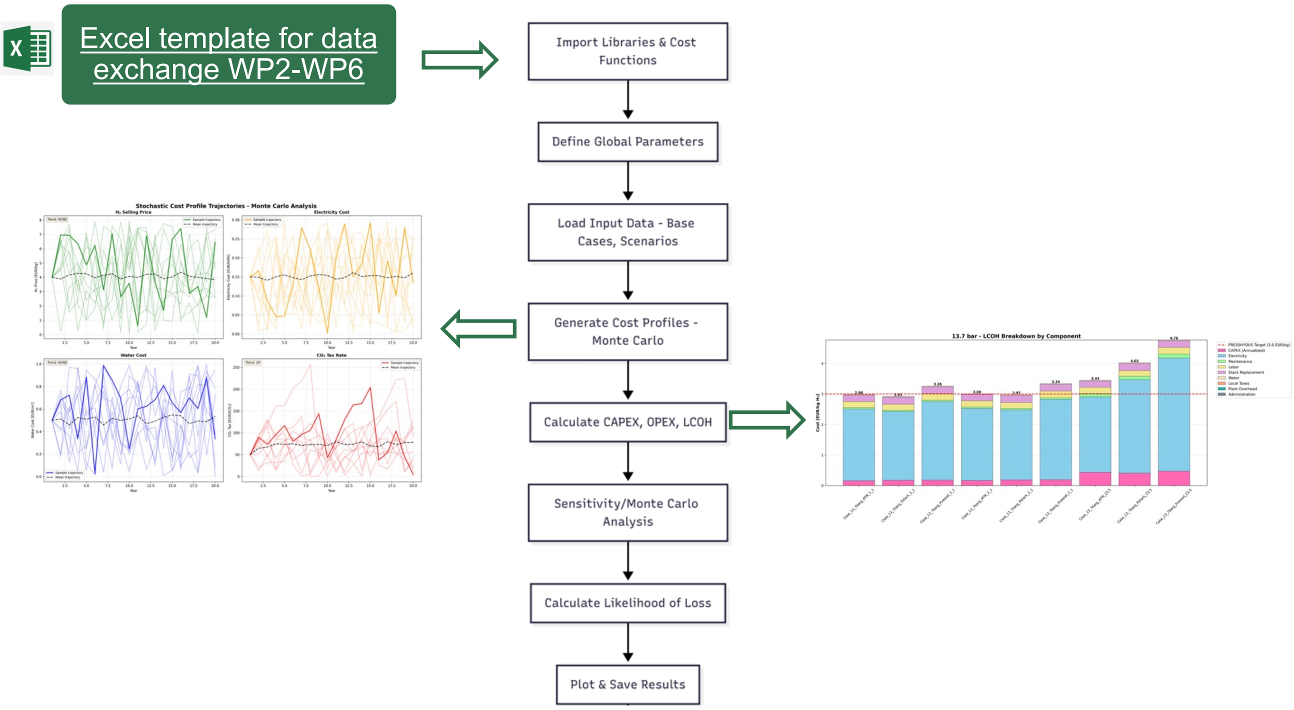

Figure 2. *TEA framework workflow.*

Individual equipment costs are estimated using the modular costing methodology of Turton et al. [4], where the base purchased cost C°_{p} is computed from correlations of the form $\log_{10}(C^{\circ}_{p}) = K_1 + K_2 \cdot \log_{10}(A) + K_3 \cdot [\log_{10}(A)]^2$, with A being the capacity parameter (shaft power for compressors, heat transfer area for heat exchangers, or volume for pressure vessels). All base costs are escalated to 2024 using the Chemical Engineering Plant Cost Index and converted to EUR. The bare module cost is obtained by multiplying C°_{p} by a bare module factor F^{IM} that accounts for material of construction and operating pressure.

The SOEC stack cost is assumed to be 900 EUR/kW [5], with a 20% increase applied for P-stack configurations due to the higher sealing and interconnections costs as suggested in [1]. Total CAPEX is the sum of all bare module costs plus a 40% indirect-cost allowance for engineering, procurement, construction, and contingency. Annual OPEX includes electricity with a baseline price of 70 EUR/MWh, maintenance (2.5% of CAPEX), labor, water (2.0 EUR/m³), and additional charges computed following Turton's methodology: local taxes (3.2% of CAPEX), plant overhead (70.8% of labor + 3.6% of CAPEX), and administration (17.7% of labor + 0.9% of CAPEX) [4]. Stack replacement occurs every 3 years at 80% of initial cost; the present value of all replacements over the 20-year lifetime is discounted at 6% and annualized. The LCOH (EUR/kg) is the sum of the annualized CAPEX and total annual OPEX divided by annual hydrogen production.

The Monte Carlo sensitivity analysis generates 10,000 stochastic cost trajectories over the 20-year project horizon using partially monotonic random trends for electricity price, water cost, H_2 selling price, and CO_2 tax. Each trajectory allows random year-to-year fluctuations while optionally following an upward or downward trend, controlled by a trend probability parameter. Figure 3 presents a snapshot example of these trajectories. The resulting incremental net present value (iNPV) is computed for each pressurized configuration relative to the atmospheric (ATM) baseline, enabling a probabilistic evaluation of investment performance under market uncertainty.

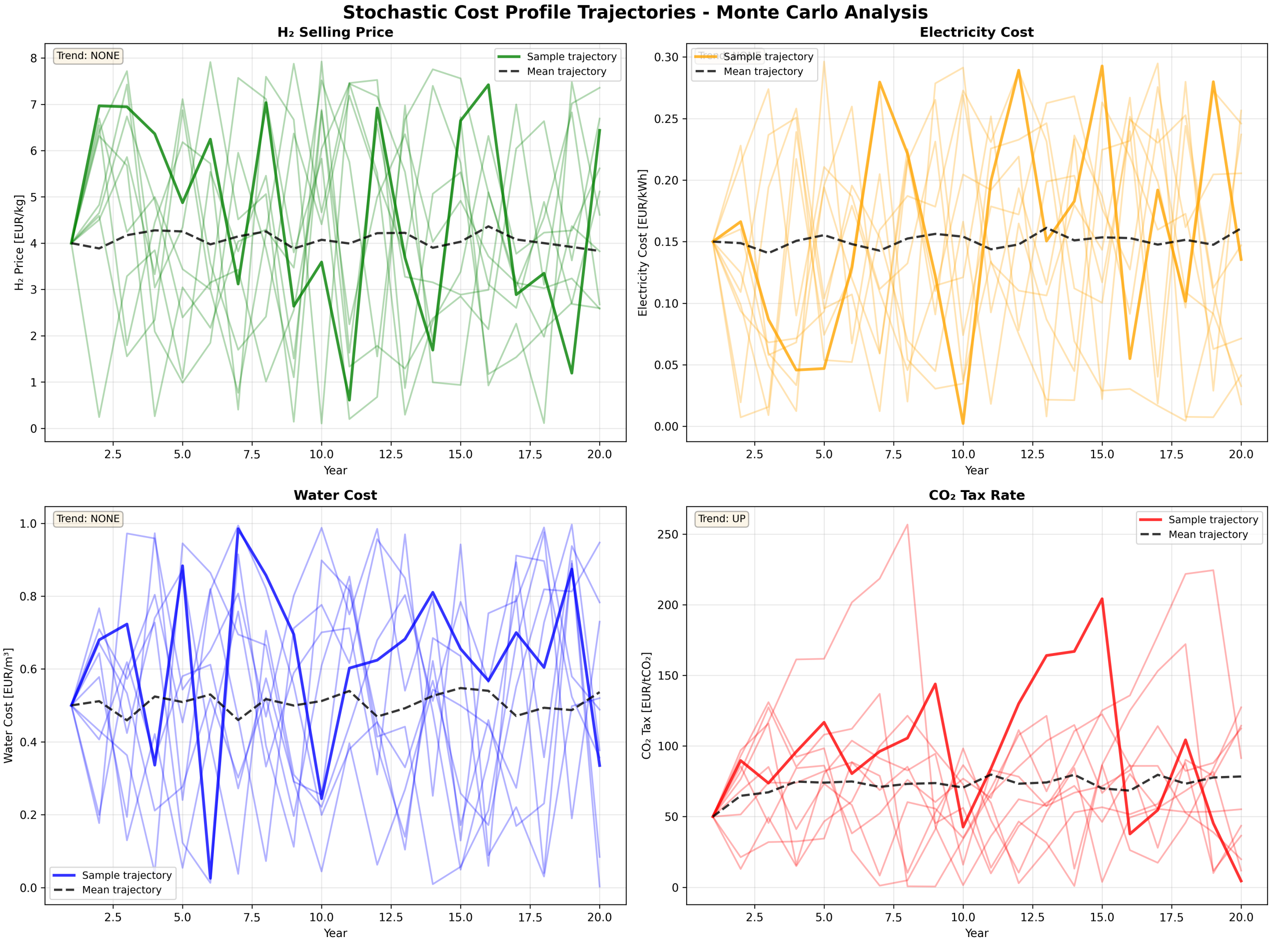

Figure 3. *Snapshot example of a stochastic price distribution*

A sensitivity analysis was performed considering five grid decarbonization scenarios defined in Fig. 4, ranging from the current French grid (44 gCO_2/kWh at 70 EUR/MWh) to a near-zero carbon scenario (3 gCO_2/kWh), with electricity costs scaled proportionally to carbon intensity. For each scenario, the LCOH is recalculated to assess the economic performance to the evolving energy transition landscape.

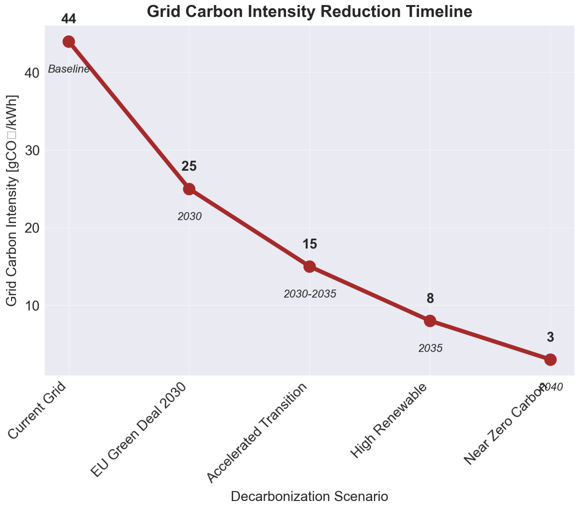

Figure 4. *Grid carbon intensity scenarios.*

4. Results and discussion

4.1. LCOH results

From Fig. 5, it can be seen that the SOEC stack dominates power consumption across all cases (65–97%). At 4.0 barg, its contribution remains nearly constant (~95–97%) regardless of the configuration or air sweeping ratio, indicating that at this scale (15 kg/h H_2, fuel use case) auxiliary equipment has a negligible impact on total power demand. At 13.7 barg (Steel-DRI, 14,000 kg/h H_2), the stack share progressively decreases as the air circulation increases: from ~94–95% at the 1:1 ratio to ~91–93% at the 2:1 ratio, and down to 68% and 65% for the 23.5 mol% O_2 target scenarios. This reduction is driven by the growing demand of the air compressor, which reaches up to 35% of total power in the 23.5 mol% case, as achieving a lower outlet O_2 concentration requires substantially higher air flow rates.

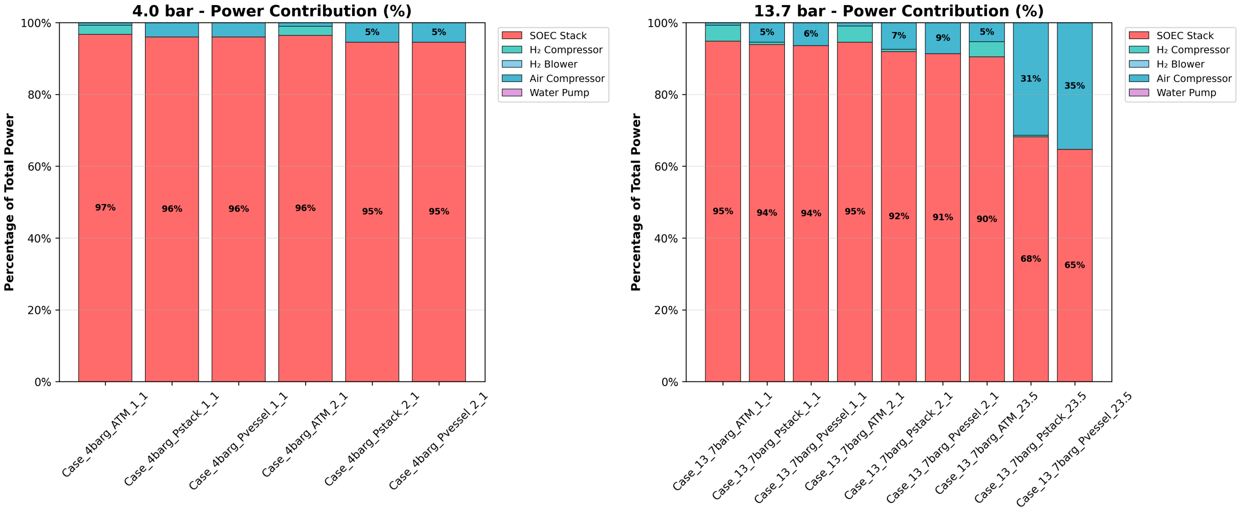

Figure 5. *Power consumption contribution.*

The CAPEX breakdown (Fig. 6) shows that the heat exchangers are the dominant cost component at 4.0 barg, accounting for 89–93% of total CAPEX, with the SOEC stack contributing to 6–8% and minor shares from other equipment. At this scale (15 kg/h H_2, fuel use case), the cost shares remains unchanged across configurations (ATM, P-stack, P-vessel) and air sweeping ratios (1:1 and 2:1), reflecting the limited impact of pressurization equipment at small scale. At 13.7 barg (Steel-DRI, 14,000 kg/h H_2), the SOEC stack share decreases from ~74% in the 1:1 ratio cases to as low as 26% at higher air circulation rates, as the air compressors become increasingly significant contributors.

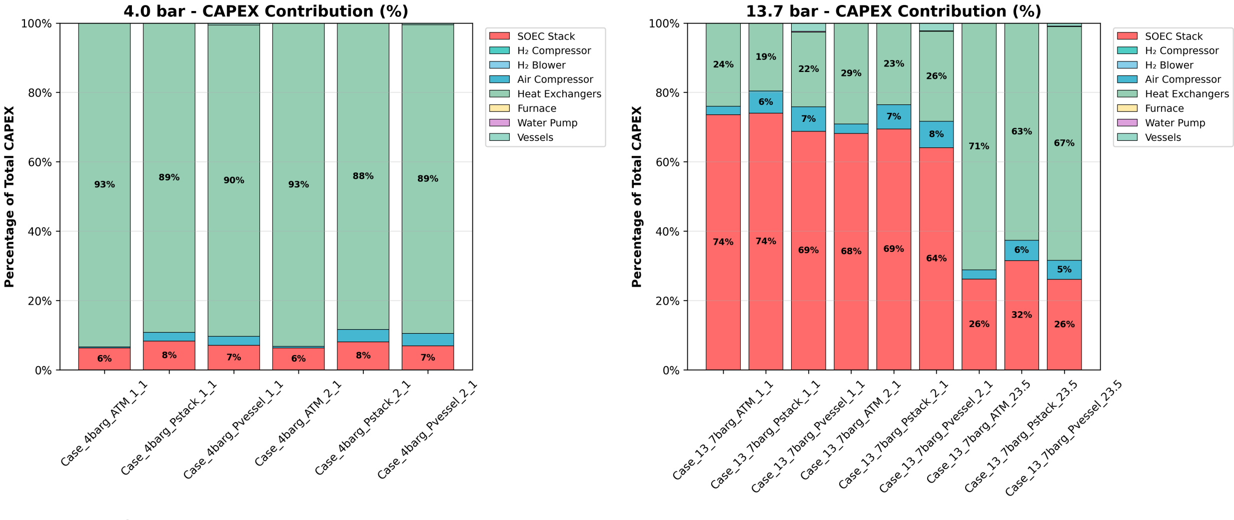

Figure 6. *CAPEX breakdown.*

Electricity is the dominant OPEX contributor in all cases (see Fig. 7), representing 72–73% at 4.0 barg and 82–86% at 13.7 barg. Stack replacement remains a secondary contributor in both pressure levels, together with labor and maintenance costs.

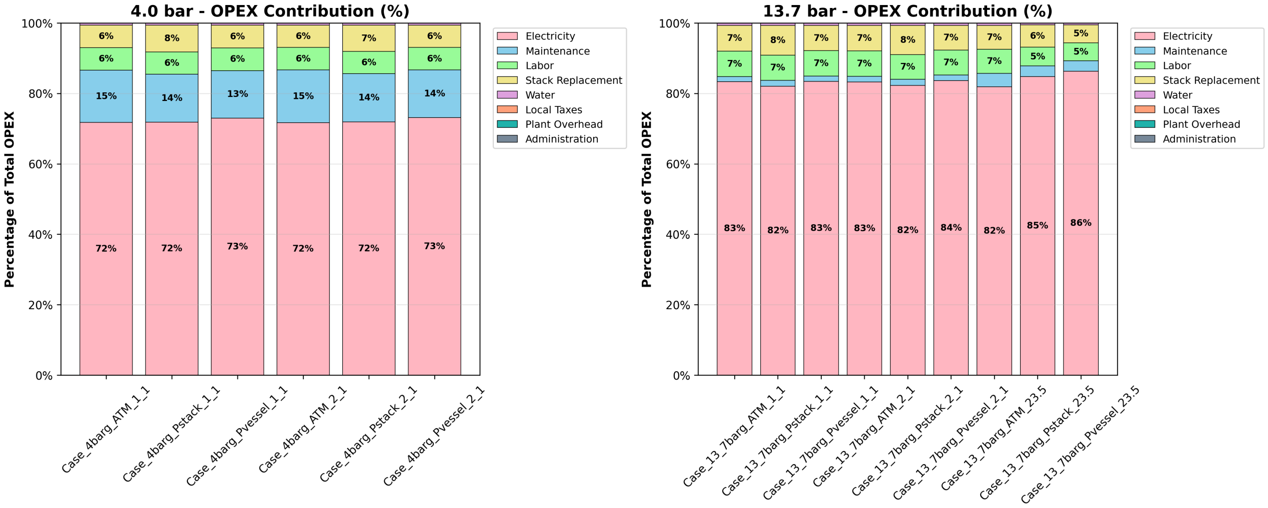

Figure 7. *OPEX breakdown.*

The LCOH breakdown in Figs. 8 and 9 shows that electricity and annualized CAPEX are the two main cost drivers across all scenarios. At 70 EUR/MWh (Fig. 8), the LCOH ranges from ~2.91 to 4.76 EUR/kg H_2, with several 13.7 barg cases falling below or near the target of 3.0 EUR/kg, while all 4.0 barg cases exceed it (~4.87–5.26 EUR/kg). At 100 EUR/MWh (Fig. 9), costs increase across the board (3.87–6.35 EUR/kg), and only the lowest-pressure 13.7 barg cases remain close to the target. The significant cost gap between 4.0 and 13.7 barg is driven not only by reduced downstream compression requirements at higher operating pressure, but also by the scale effect — the 13.7 barg cases correspond to the Steel-DRI use case (14,000 kg/h H_2), which benefits from economies of scale compared to the H_2 as fuel case at 4.0 barg (15 kg/h H_2). Across both pressure levels, the air sweeping strategy also influences the LCOH: increasing the air circulation ratio from 1:1 to 2:1 raises costs due to higher air compressor power and equipment sizing, while the 23.5 mol% O_2 target strategy (only at 13.7 barg) leads to the highest LCOH values, as it requires the largest air flow rates to achieve a lower outlet O_2 concentration. This confirms that electricity price, production scale, operating pressure, and air management strategy are all critical levers for LCOH competitiveness.

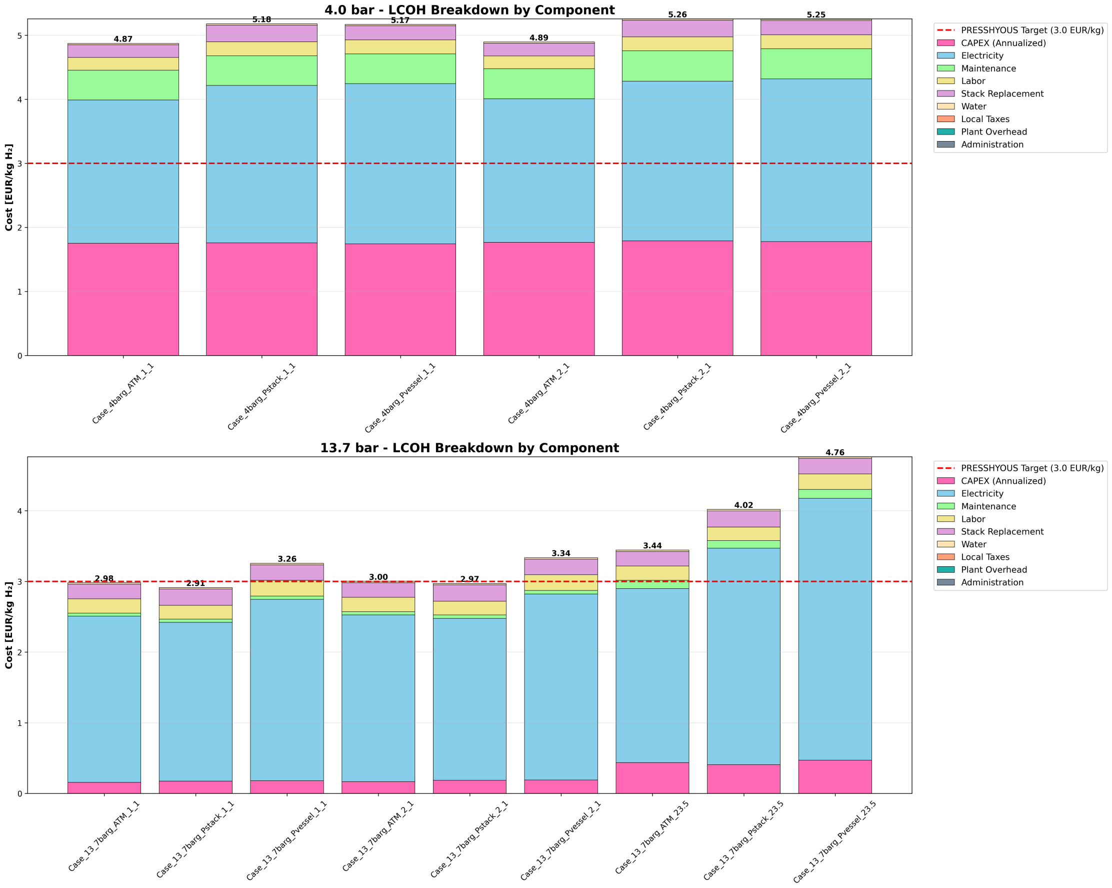

Figure 8. *LCOH breakdown. Elec price: 70 EUR/MWh.*

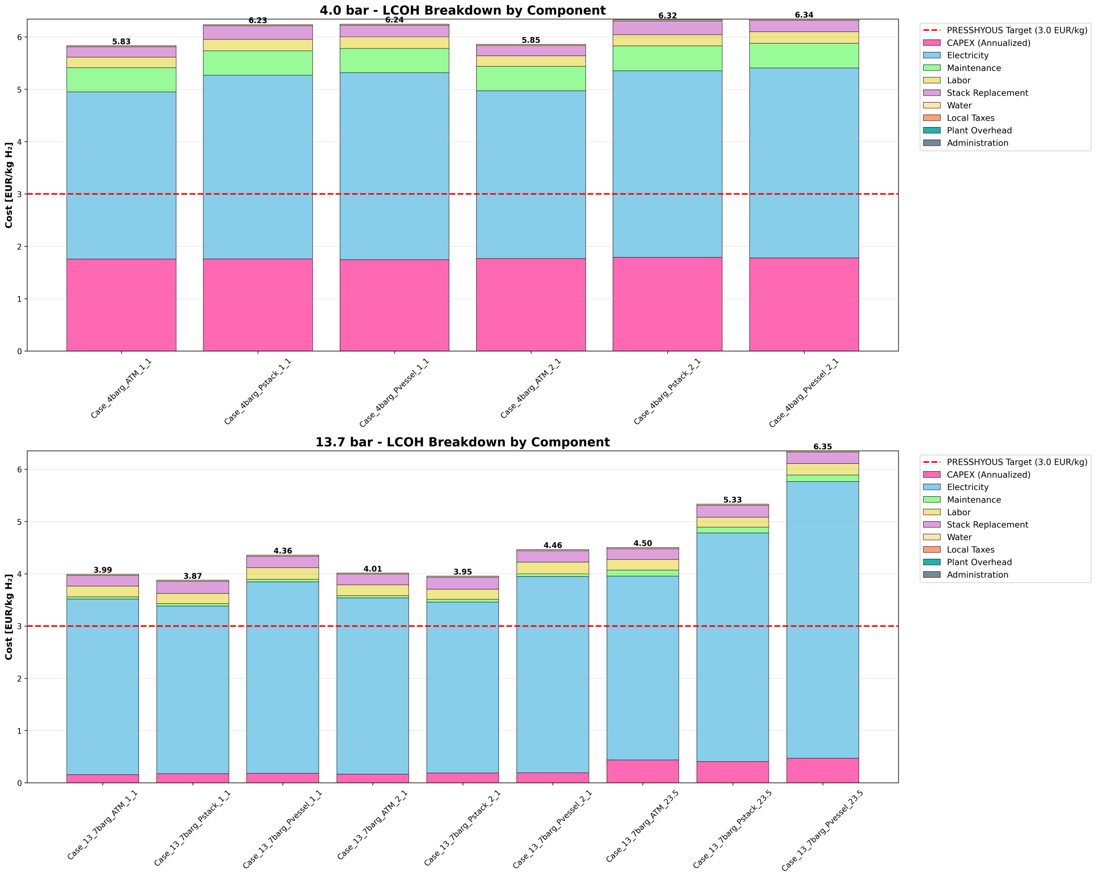

Figure 9. *LCOH breakdown. Elec price: 100 EUR/MWh.*

For the sensitivity considering the different grid carbon intensity scenarios (Fig. 10), it can be seen that at 4.0 barg, all cases converge toward ~4.5–5.0 EUR/kg H_2, remaining well above the target of 3.0 EUR/kg even under the most favorable grid scenario. In contrast, the 13.7 barg cases (Steel-DRI) exhibit a much steeper cost reduction, with the P-stack and ATM configurations at 1:1 air ratio already approaching the 3.0 EUR/kg target under the current grid, and reaching as low as ~1.5 EUR/kg under near-zero carbon conditions. However, the more air-intensive scenarios (2:1 and 23.5 mol% O_2) require at least an accelerated energy transition to reach the target, highlighting that the combination of pressurized operation, large production scale, moderate air sweeping strategies, and a progressively decarbonized grid is key to meeting the LCOH objective.

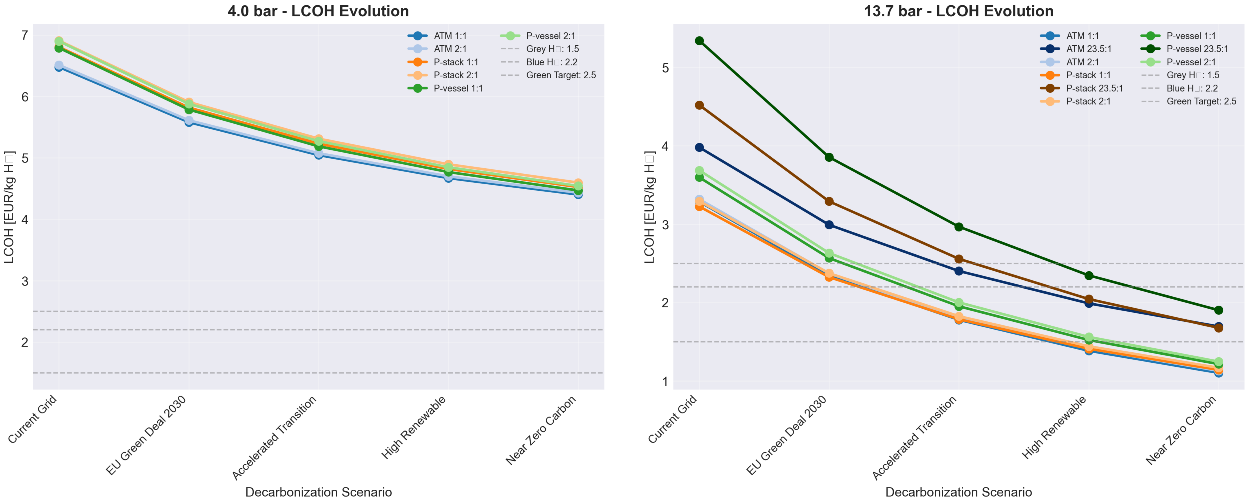

Figure 10. *Sensitivity on grid carbon intensity.*

The Monte Carlo analysis comparing pressurized SOEC configurations against the atmospheric (ATM) base case at 13.7 barg (Figure 11) reveals a stark contrast between the P-stack and P-vessel approaches. The P-stack configuration yields consistently positive iNPV distributions, with 100% probability of gain for both sweeping air strategies demonstrating robust economic viability under stochastic energy price and CO_2 tax variations. On the other hand, the P-vessel configuration shows entirely negative iNPV distributions with 0% probability of gain, indicating that the additional capital cost of pressure vessels is not recovered over the 20-year horizon. These preliminary results suggest that pressurizing the SOEC stack itself is the economically preferred pathway, while enclosing the stack in a pressure vessel is not financially attractive under the considered assumptions.

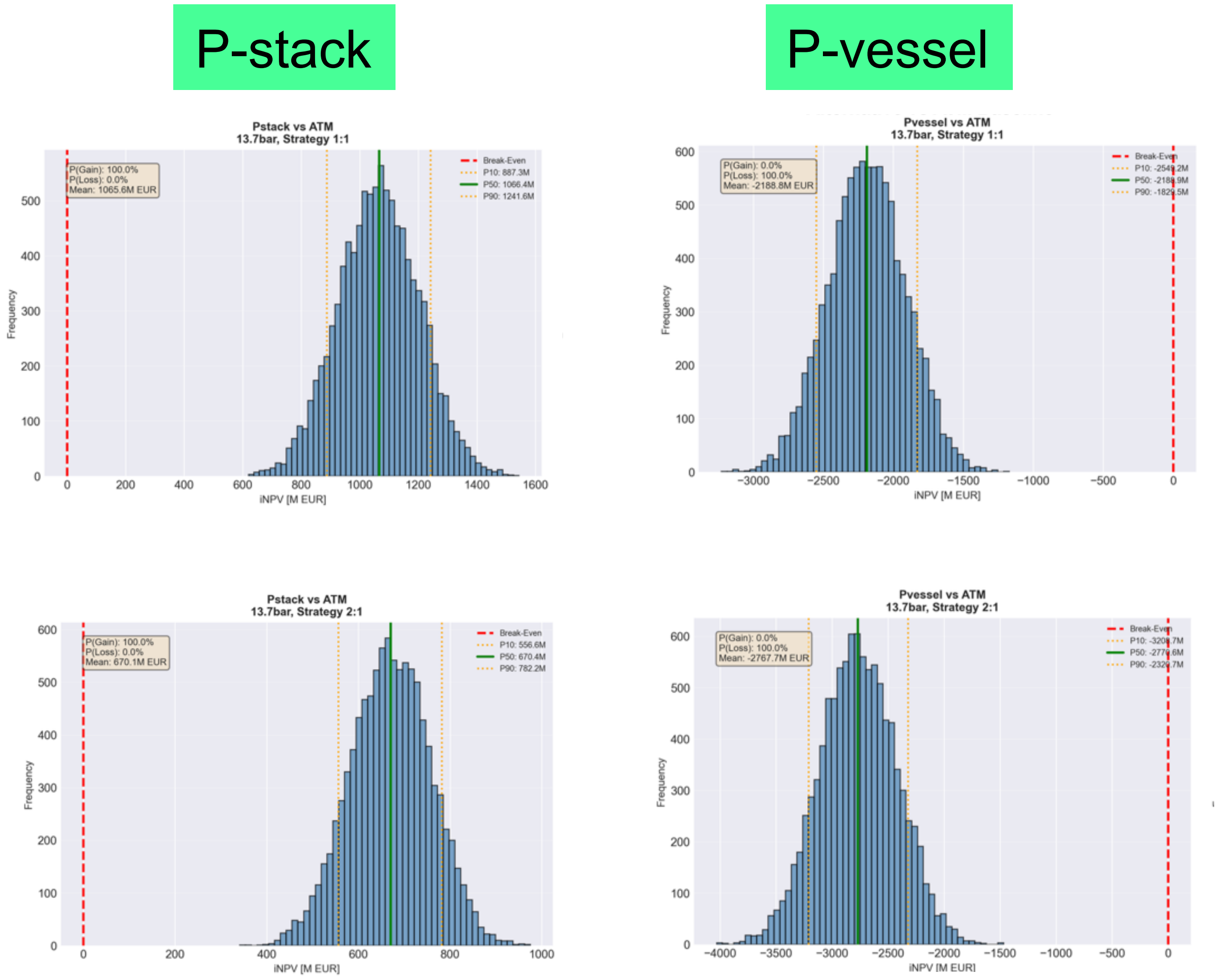

Figure 11. *Incremental net present value (iNPV) distribution.*

5. Conclusion

This study presented a comprehensive techno-economic assessment of pressurized SOEC hydrogen production systems, evaluating fifteen plant configurations across two industrial use cases (Steel-DRI at 13.7 barg and H_2 as fuel at 4 barg) and three technology variants (ATM, P-stack, P-vessel).

The deterministic analysis revealed that the SOEC stack dominates power consumption across all configurations (65–97%), while electricity represents the largest OPEX component (72–86%). At an electricity price of 70 EUR/MWh, the LCOH for the large-scale DRI case ranges from 2.91 to 4.76 EUR/kg, with the P-stack and ATM configurations at 1:1 air ratio approaching the target of 3.0 EUR/kg. In contrast, the small-scale fuel case (15 kg H_2/h at 4 barg) yields significantly higher costs (4.87–5.26 EUR/kg), confirming that economies of scale are the dominant cost driver rather than the pressurization strategy itself.

The air management strategy was identified as a critical economic lever: increasing the air-sweep ratio from 1:1 to 2:1 raises the LCOH due to higher air compressor power and equipment sizing, while the 23.5 mol% O_2 target scenario incurs the highest costs, as it requires substantially larger air flow rates. Under progressive grid decarbonization scenarios, the 13.7 barg DRI configurations exhibit a steep cost reduction, reaching LCOH values as low as 1.5 EUR/kg under near-zero carbon conditions, while the 4 barg cases remain above the 3.0 EUR/kg target regardless of grid scenario.

The Monte Carlo analysis (10,000 simulations) confirmed the robustness of these conclusions under stochastic electricity price and CO_2 tax trajectories. Incremental NPV comparisons between pressurized and atmospheric configurations indicate that the economic advantage of pressurized SOEC deployment is contingent on the combination of large production scale, moderate air-sweep ratios, and electricity costs below 40 EUR/MWh. These findings underscore that pressurized SOEC technology must be strategically matched to application requirements, with high-throughput, moderate-pressure industrial applications offering the clearest pathway to economic viability.

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Nomenclature

Symbols

A	capacity parameter (shaft power, area, or volume)
C°_{p}	base purchased equipment cost
F_{a}	base scaling factor,
F^{IM}	bare module factor,
K_1, K_2, K_3	cost correlation constants,

Subscripts and superscripts

BM	bare module
BoP	balance of plant

Abbreviations

ATM	atmospheric SOEC configuration
BoP	balance of plant
CAPEX	capital expenditure
DRI	direct reduced iron
iNPV	incremental net present value
LCOH	levelized cost of hydrogen
OPEX	operating expenditure
P-stack	pressurized stack configuration
P-vessel	pressure vessel configuration
SOEC	solid oxide electrolysis cell
TEA	techno-economic assessment

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